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CERN Intersecting Storage Rings (ISR)

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It has been realized for many years that it would be possible to obtain a glimpse into a much higher energy region for elementary-particle research if particle beams could be persuaded to collide head-on.

To explain why this is so, let us consider what happens in a conventional accelerator experiment. When accelerated particles have reached the required energy they are directed onto a target and collide with the stationary particles of the target. Most of the energy given to the accelerated particles then goes into keeping the particles that result from the collision moving in the direction of the incident particles (to conserve momentum). Only a quite modest fraction is "useful energy" for the real purpose of the experiment—the transformation of particles, the creation of new particles. For example, at the full energy of the CERN 28 GeV synchrotron, about 7 GeV is useful energy. The useful energy can, in the relativistic approximation, be written

$$E_{c.m} \simeq \sqrt{mc^2E}$$

Thus, a 300-GeV proton accelerator gives about 24 GeV of useful energy.

But if particles of the same energy were made to collide head-on, *all* their energy would be useful, since none would be needed to conserve momentum to keep things moving in a particular direction. The interest of the CERN Intersecting Storage Rings then lies in the prospect of colliding 28 GeV protons head-on and having 56 GeV of useful energy available. To achieve this with a conventional accelerator would require a machine with an energy of about 1700 GeV, which is possibly beyond existing technology and certainly beyond existing financial resources.

This great leap forward in useful energy by using colliding beams has to be qualified by repeating that they will provide only a glimpse into a much higher energy region rather than a broad look. The conventional accelerator is a prolific source of many types of particle and it can be used to investigate interactions involving protons, antiprotons, kaons, pions, and neutrinos. With colliding beams, the interaction is limited to that of the beam particles—for the CERN ISR this means the proton–proton interaction.

The history of colliding-beam devices really began in 1956 when the group at the Midwestern Universities Research Association (MURA) in the United States put forward the idea of stacking particle beams in circular accelerators. Before that time, people working with particle accelerators had, of course, speculated about the possibilities of reaching high center-of-mass energies with colliding beams, but such ideas did not appear to be realistic with the particle densities available in beams of normal accelerators. But the MURA proposals for particle stacking changed the prospect significantly and opened up the possibility of making two intense beams of protons collide with sufficiently high interaction rates for feasible experimentation in an energy range otherwise unattainable by known techniques except at enormous cost.

A group at CERN started investigating this possibility in 1957, first studying a special two-way fixed-field alternating gradient (FFAG) accelerator and then, in 1960, turning to the idea of two intersecting storage rings that could be fed by the CERN 28 GeV proton synchrotron (CERN-PS). This change in concept for these initial studies was stimulated by the promising performance of the CERN-PS from the very start of its operation in 1959.

After an extensive study that included building an electron storage ring (CESAR) to investigate many of the associated problems, a proposal was made in 1964 to the CERN Council for construction of two intersecting storage rings (ISR) for 28 GeV protons. The project was approved the following year and construction was started early in 1966; France had already made available a piece of land, across the border from CERN's Swiss site, where the ISR could be built.

GENERAL DESCRIPTION OF THE ISR

The ISR consist of two concentric rings of magnets, 300 m in diameter, in which protons travel in opposite directions. The rings are built in a circular underground tunnel some 200 m away from the 28 GeV proton synchrotron. The two rings are not exactly circular, but are interlaced so that they intersect at eight points, called intersection regions, where the beams can be brought into collision. A schematic representation of the configuration and of the beam paths can be seen in Fig. 1, and the main parameters of the rings are given in Table 1.

Protons are accelerated to the required energy (which can be between 11 and 26 GeV) in the CERN-PS. They are then ejected by a fast-ejection system into a transfer channel where a magnet system guides them towards the ISR. This channel forks in two and, depending on whether a bending magnet at the fork is switched on or not, the protons travel along further channels to the left or right to enter one or the other of the rings. The protons are injected into an ISR ring by a fast-injection system, so that they initially travel close to the inside wall of the ring's vacuum chamber.

If simply one pulse was taken from the PS containing, say, 10^{12} protons and fed into one ring, and another similar pulse was fed into the other ring orbiting in the opposite direction, the number of collisions per second that would take place when the beams met in the intersection regions would be unacceptably small. Experiments at conventional high-energy accelerators, such as the CERN-PS, study interactions produced by the beams on, say, a liquid hydrogen target with typical collision rates of the order of 10^5 per second. The ISR has been designed to achieve a similar figure when the beams collide.

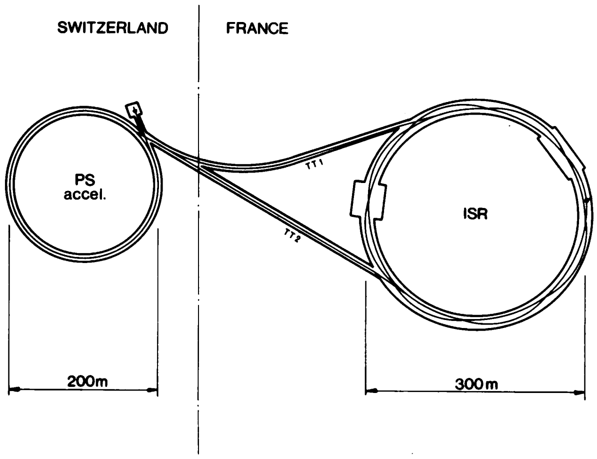

FIG. 1. Layout of the intersecting storage rings (ISR).

A measure of intensity for colliding-beam devices is a parameter known as the luminosity, L, defined as the figure by which one has to multiply a cross section (for a given type of interaction) to arrive at the number of events per second. As an example, one could ask what luminosity would be required to reach a total p–p interaction rate per second of 10^5, similar to the typical figure given above for secondary beams on a hydrogen target. Assuming a total p–p cross section of 40 mb, we find that an $L = 2.5 \times 10^{30}$ cm^{-2} s^{-1} would give 10^5 interactions per sec.

The ISR design aimed, in fact, at $L \simeq 4 \times 10^{30}$ cm^{-2} s^{-1}. To achieve this, it is necessary to increase the intensity of the two orbiting beams so that they each contain 4×10^{14} protons, which is equivalent to a circulating current in each ring of about 20 A. Beams of this intensity are achieved by stacking many successive pulses from the CERN-PS next to one another.

For this purpose a radio-frequency system is needed. After the first pulse has been injected, this RF system accelerates the protons just enough to move the particles from their injection orbit to an orbit nearer the outside of the vacuum chamber. When this acceleration has been done, the injection orbit is free to receive the next pulse which, in its turn, is accelerated and moved to an orbit only a fraction of a millimeter from where the first pulse was left. This stacking process can be repeated again and again, in fact, about 400 times in each ring, to create a stacked beam about 70 mm wide with the intensities mentioned above. Fig. 2 illustrates the stacking process and how one gradually fills the aperture available in the vacuum chamber. With 400 pulses stacked there will be a momentum spread of 2% across the beam.

The protons can continue to circulate in the rings and colliding-beam experiments can be performed for as long as 36 hr before calling on the CERN-PS again for a refill.

Most of the major problems in constructing the ISR arose

TABLE 1. *Main parameters of the ISR*

Number of rings	2
Circumference of rings	942.66 m
Number of intersections	8
Length of long straight section	16.8 m
Intersection angle at crossing points	14.7885°
Maximum energy of each beam	28 GeV
Hoped for luminosity (per intersection)	4×10^{30} cm^{-2} s^{-1}
Magnet (one ring)	
Maximum field at equilibrium orbit	12 kG
Maximum current to magnet coils	3750 A
Maximum power dissipation	7.04 MW
Number of magnet periods	48
Number of superperiods	4
Total weight of steel	5000 tons
Total weight of copper	560 tons
RF system (one ring)	
Number of RF cavities	6
Harmonic number	30
Center frequency of RF	9.53 MHz
Maximum peak RF voltage per turn	20 kV
Vacuum system	
Vacuum chamber material	Low-carbon stainless steel
Vacuum chamber inside dimensions	160×52 mm^2
Design pressure outside intersection regions	10^{-9} torr
Design pressure inside intersection regions	10^{-10} to 10^{-11} torr

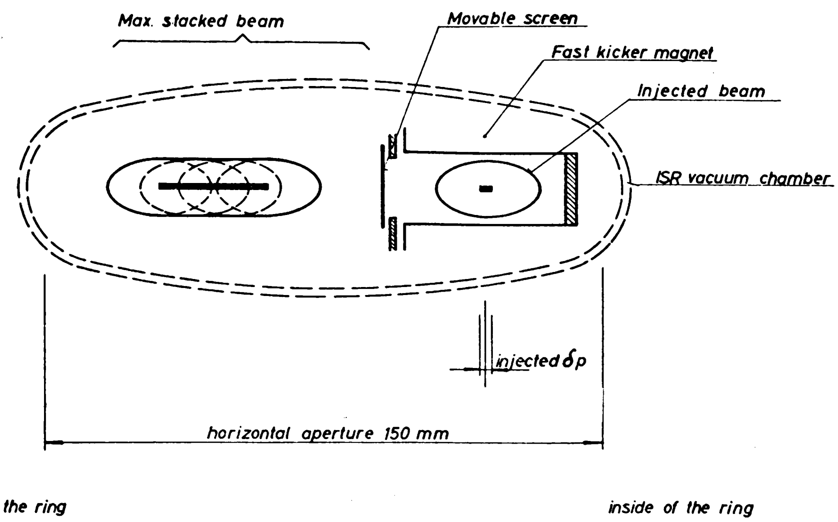

FIG. 2. Cross-section of the vacuum chamber at the position of the beam inflector, with indication of the stacking process.

because of the need to build up such intense beams of protons and to keep them orbiting in their rings for many hours. The conditions that must be established are very different from those in the conventional accelerator where the beam is in and out of the machine in periods of time of the order of one or a few seconds.

The RF system is not required to produce unusually high accelerating voltages, but has to be capable of carefully controlled voltage variations from 20 kV at injection to tens of volts at the end of the stacking process. The magnet system has to provide a very precise field configuration to guide and focus the beams and has to incorporate a full range of correction possibilities to cope with any deviations from the ideal in the beam paths. The main magnets have also to provide "good field" across the full aperture of the vacuum vessel (over 150 mm horizontally), up to a field strength of 12 kG on the equilibrium orbit.

The demands placed on the vacuum system are particularly severe. If beams are to be retained in the rings for many millions of turns without serious loss in intensity, not only must the magnetic guide fields keep them well under control, but the number of residual gas molecules that the beams meet must also be very small to avoid scattering protons out of the beams. In the conventional accelerator, pressures around 10^{-6} torr are adequate; in the ISR this has to be pushed down to 10^{-10} torr (a pressure feasible only in small laboratory-bench set-ups just a few years ago). This ultra-high vacuum must be held throughout a vacuum chamber that includes thousands of joints and has a total length (in the two rings together) of 2 km. This is by far the biggest ultra-high vacuum system in the world.

Even with this low pressure the scattering caused by the residual gas molecules in the vacuum chamber will make the beams "blow up" significantly in size over 20 hr. To allow for this increase in size, in addition to deviation of the beams that could be caused by imperfections in the magnetic field, the vacuum vessel's aperture was set at 160 mm horizontally and 52 mm vertically.

Another indication that the stability of the intense beams is fragile is that "clearing electrodes" have to be installed to sweep away the electrons liberated when the beams ionize the residual gas. These electrons would tend to neutralize the positive charge in the beams and thus upset the delicate balance between the defocusing electric force acting within the beams and the focusing magnetic force that the fast-moving charges set up. Without these clearing electrodes only a fraction of the planned beam intensity could be stored. Other possible sources of instabilities were investigated during the design period and were judged to be either not troublesome or of such a nature that they could be kept under control by

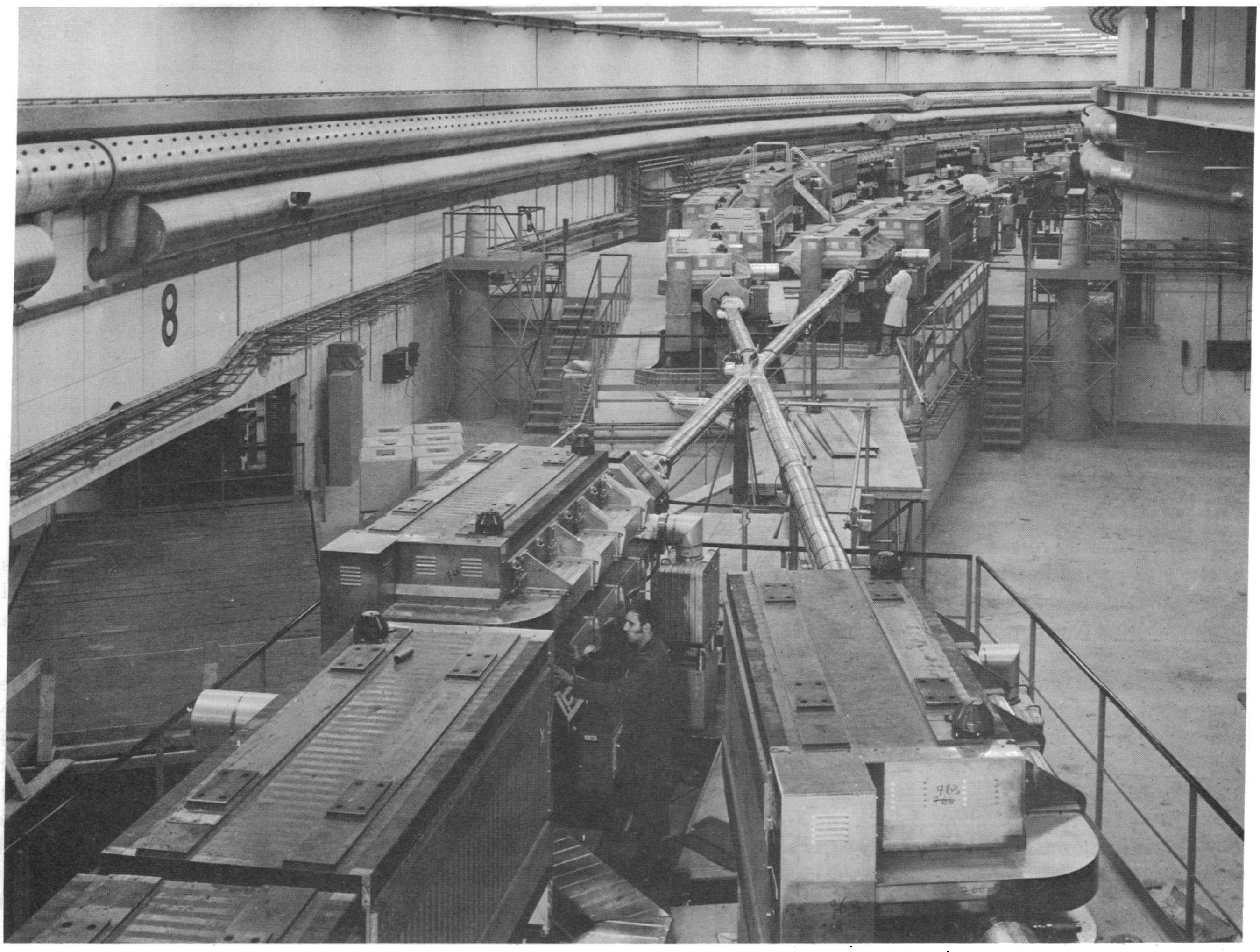

FIG. 3. View of the inside of the ISR tunnel with magnets and other machine components installed.

FIG. 4. Aerial view of the ISR.

special remedies, up to the planned beam currents. This judgment has been confirmed in practice, although some difficulties with beam instabilities have occurred.

Fig. 3 shows a photo of the actual machine in the tunnel with one of the intersection regions before experimental equipment was moved in. Fig. 4 is the ISR seen from the air.

PRESENT PERFORMANCE AND ITS LIMITATIONS

The beam intensities in the ISR are far above normal beam intensities in proton accelerators and one would, therefore, expect different beam behavior; in particular, one might expect collective phenomena to be very important. Furthermore, the ISR has some special requirements, especially with respect to beam lifetime and background radiation, that are unimportant for ordinary accelerators. The following is a summary of the various aspects of the ISR performance.

Lifetime

At low stacked currents (< about 2 A) the observed loss rates of the beams are normally as low as a few parts per million per minute, in good agreement with calculated loss rates due to nuclear scattering on the remaining gas. At higher currents, the loss rates have a tendency to increase such that other loss mechanisms must play a role, and some will be touched upon later. However, recently we have been able by very careful "shaving" of the beams to reduce the losses nearly to nuclear scattering up to about 8 A of circulating beam. Above this current, the loss rate increases rapidly and goes at present to infinity at around 11–12 A. However, this is associated with a vacuum deterioration that will be described in more detail in the next section.

Intensity limitations

The highest current stacked until now (October, 1972) is 12.8 A. In the process of bringing the intensity up, several interesting phenomena related to high intensity have been observed.

Transverse Coherent Instability. During the early tests, we found an intensity limitation appearing around 3 A, a value perhaps a little lower than expected. The frequency of coherent signals induced in pick-up stations, and the fact that the instability can be influenced by sextupole fields, show that it is a low-frequency instability that is driven by the resistivity and inductivity of the vacuum chambers. Since we started applying appropriate sextupole components to the magnetic field, this transverse coherent instability has hardly caused difficulty, although we have provoked it artificially in order to study it. Since, for various reasons, we cannot apply enough

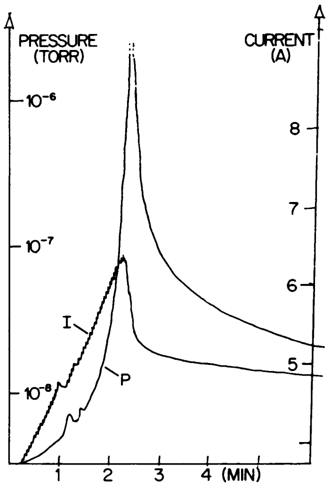

FIG. 5. Example of a pressure increase caused by the stacked beam.

sextupole field to suppress this instability much beyond 10–15 A, a feedback system will be installed to provide additional damping.

Pressure Bumps. Another intensity limitation occurred, however, at higher currents. An example of this effect is shown by the curve marked **I** in Fig. 5. It differed from the previous one mainly by the fact that it did not seem to be associated with coherent oscillations. Further, it seemed to be rather insensitive to magnetic-field shape, energy, and stacking conditions (beam shape, density, etc.). The most striking feature is that it is always associated with a severe vacuum deterioration that follows the beam current rather than the losses. Fig. 5 also shows a typical recording of the pressure, and one notices the relation between this pressure and the beam intensity. The places where these "pressure bumps" occur are more or less fixed. We have now baked most of the vacuum system to 300°C instead of the 200°C that was usual at the beginning. This practice resulted in a marked improvement, as illustrated in Fig. 6, which shows how the maximum stacked current has increased with time as various remedies have become effective. It is hoped that further improvements will come as a result of the increased pumping speed we shall obtain from a large number of sublimation pumps that are in the process of being installed. We are also trying various methods for further improving surface conditions of the vacuum chamber's walls.

The mechanism creating these pressure bumps seems to be gas desorption from the chamber walls due to bombardment of the ions created in the residual gas inside the beam. The first bombardment releases gas, which creates more ions, thus increasing the bombardment further, and so on. Beyond a certain critical beam current this results in an avalanche of pressure increase. When the pressure rises catastrophically somewhere, the beam is automatically dumped.

However, as already mentioned, anomalous loss rates are observed well below the critical current, and it is believed that these are also caused by the pressure increases, and by a mechanism that is not normal gas scattering since the average pressure is still too low for gas scattering to be important. The various theories for these losses are considered to be outside the scope of this paper, and further experimental data are needed before firm conclusions can be drawn.

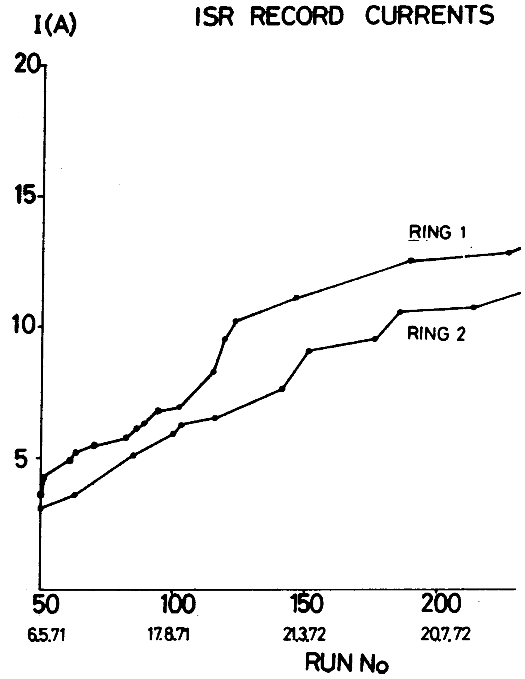

FIG. 6. Maximum stacked proton currents as a function of time.

The ISR as a facility for experiments

In this section we shall take a brief look at some machine conditions of special interest for the physics experiments.

Luminosity. The beams can be steered vertically very accurately in the intersection regions, and such steering is used to optimize the conditions of the colliding beams in preparation for physics runs. The aim is to provide the best luminosity and least background at each of the intersections used for experiments. During the process, good measurements are obtained for the effective vertical dimensions of the beams (the luminosity is inversely proportional to the effective beam height). Although the original design assumed effective beam heights of 10 mm, the actual heights are about 5 mm and, recently, by scraping the beams, the effective beam height has been further reduced to about 3 mm.

By such means, luminosities for physics runs have reached values of

$$L \simeq 2 \times 10^{30}\ \mathrm{cm^{-2}\ s^{-1}}$$

with 7–8 A in each beam.

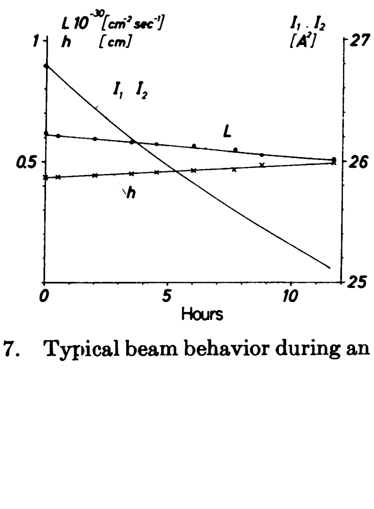

FIG. 7. Typical beam behavior during an 11-hr run.

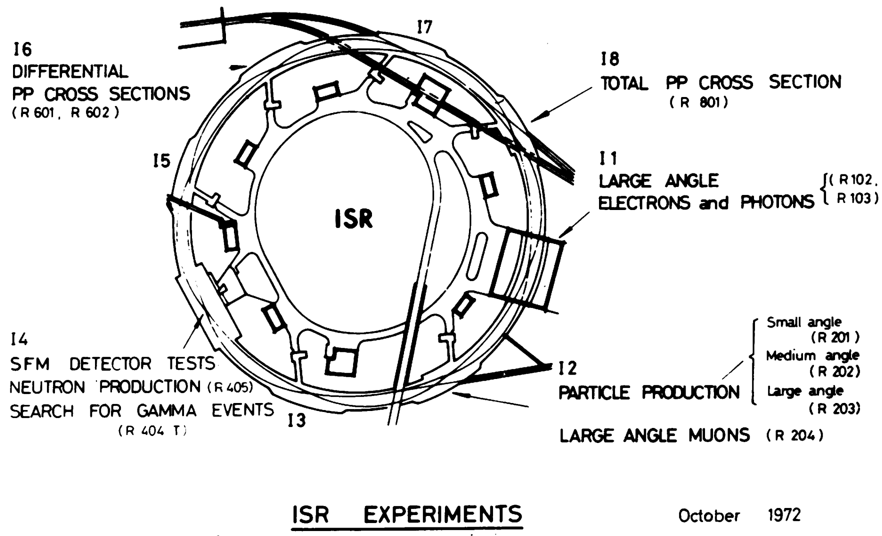

FIG. 8. Placing of experiments in the various intersection regions.

Background. The amount of background radiation is variable in the ISR, depending strongly on the stacking conditions and optimization procedures. In general, low background can be achieved up to the highest beam currents to which we can stack without encountering vacuum difficulties, i.e., 7–8 A. There is still much to learn about how to minimize

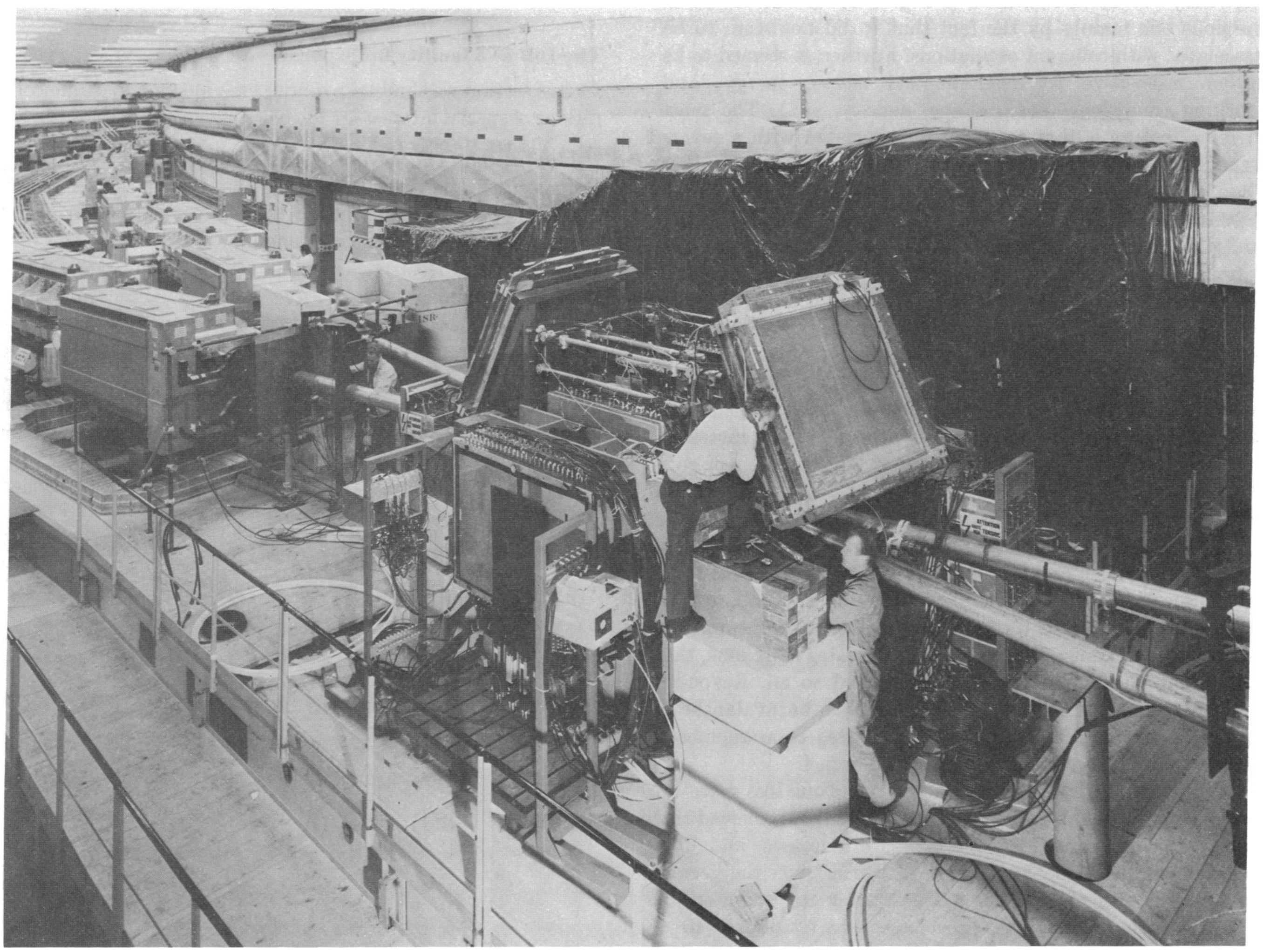

FIG. 9. Experimental equipment around an intersection region.

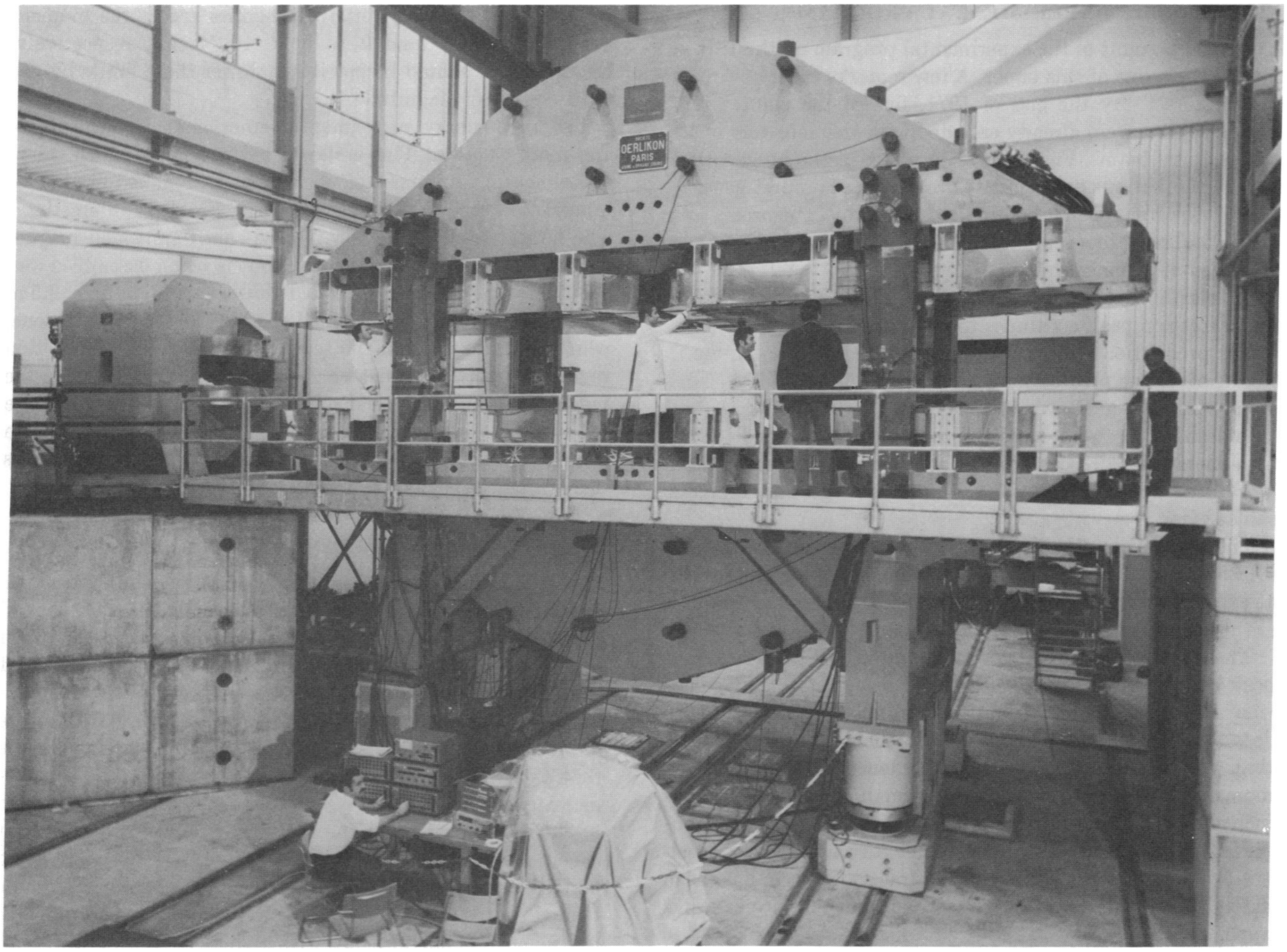

Fig. 10. Large analyzing magnet ready for tests. The magnetic field goes in one direction in the left part of the magnet and in the opposite direction in the right part.

background and to keep it low during long runs. Various scraping procedures to take away beam halo have been used with very encouraging results.

Background conditions are altogether better than we dared hope for during the design of the ISR, mainly due to the good vacuum. This has facilitated the experimental use of the ISR.

Length of Runs. A typical mode of operating the ISR is as follows: to start up in the morning and have a day of machine studies, using either 4 bunches (out of 20) per pulse from the CERN-PS or the full 20-bunch CERN-PS pulses. Near the end of the day, a period of 2–3 hr is taken for preparation for physics, during which stacks are made to the desired intensities, the optimization procedures are carried out with checks on background, etc.; beams may be restacked if the first stacks are not acceptable. The stacked beams are then left circulating, normally for the next 11 hr, and the experimental teams take their data. During the physics runs, only three people are required to operate the ISR. The beams deteriorate rather little during such runs, although the average loss rates may be somewhat higher than the best ones quoted earlier in this paper. A typical example is illustrated in Fig. 7. There have been a few runs lasting longer than 11 hr, up to 36 hr, with reduced luminosity at the end but with still quite acceptable conditions for the physics experiments.

At present, an average of about 50 hr/week is provided for taking physics data. The aim is to give about 2000 hr/year to physics, a rate that will probably continue at least for the next year or so. Parenthetically, it should be pointed out that a fairly sizeable amount of time is needed for the ISR to be shut down for access to experimentalists' equipment, in addition to normal machine maintenance and modifications.

Energies. As stated before, the ISR can accept any energy from the CERN-PS from about 11 GeV to 26 GeV. However, normal operating energies have been standardized at four values: 11.5, 15, 22, and 26 GeV in each of the two beams. The beams can also be operated at different energies and, for one physics run, the energy was 15 GeV in one beam and 26 GeV in the other.

Beams can be accelerated in the ISR, but at the price of reduced luminosity, to higher energies whose limit is set by the magnetic fields and power supplies, i.e., to a maximum of 31.4 GeV at the central orbit. The gain in equivalent stationary-target energy is not negligible, namely from 1500 to 2000 GeV/c.

Three physics runs have taken place at this energy of 31.4 GeV, with a luminosity of about 5×10^{27} cm^{-2} s^{-1}, and studies are in progress to increase the luminosity for these accelerated beams.

THE EXPERIMENTAL PROGRAM

A detailed account of the experimental program on the ISR is outside the scope of this paper. A few remarks may, however, be of interest. By the end of 1971, five of the eight intersection regions were already crowded with the detectors of 12 experimental teams. Fig. 8 shows in which of the intersection regions the various experiments are placed. The first generation of experiments can be grouped into four categories:

(*i*) Total p–p cross-section for the energy range of 23–53 GeV in the center-of-mass system;

(*ii*) elastic scattering, in particular to investigate whether the diffraction peak continues to shrink with energy;

(*iii*) production spectra for known particles (p, π, K, etc.), testing of scaling predictions;

(*iv*) search for unknown particles.

Preliminary results have been published or reported at high-energy physics conferences. For details, the specialized literature should be consulted, but a few general remarks can be made.

There is no drastic change in total cross-section of p–p collisions at ISR energies in comparison with previous results at existing accelerator energies. Published preliminary results are around 40 mb.

The elastic-scattering experiments show that the diffraction peak continues to shrink with increasing energy, but somewhat less than expected from the extrapolation of Serpukhov data and Regge–pole predictions. Further, it has been found that the simple exponential dependence on t, the four-momentum transfer, is limited to small values of the momentum transfer. Indications of this had already been observed from less accurate measurements at the lower accelerator energies. Recently, the diffraction curve has been extended at the ISR and a second diffraction peak has appeared.

There is already a wealth of particle production results available for $p^{\pm}$, $\pi^{\pm}$, and, to a lesser extent, $K^{\pm}$. In general terms, the production spectra show good agreement with scaling predictions by the time ISR energies are reached. Indeed, $\pi^{\pm}$ production scales rather well from 12–1800 GeV equivalent accelerator energy. However, more recent ISR results show clearly the leading-particle nature of the protons, and there is seen to be a relative abundance of large-transverse-momentum particles that exhibit a strong energy dependence.

On the search for unknown particles it can only be said that no exotic particles have been seen yet at the ISR. The experimental cross-section limits for the production of the W-boson and the quark at ISR energies are at the moment about 5×10^{-33} and 2 to 6×10^{-34} cm^2, respectively. Eventually, it should be possible to lower these limits by one to two orders of magnitude.

The high-energy experimental equipment becomes more and more complex. This is illustrated in Fig. 9, which shows experimental equipment of various kinds installed around an intersection region. (Comparison with Fig. 3 is interesting.) The largest research facility, the so-called split-field magnet (Fig. 10), is not yet in operation, but is being assembled and should be ready for use in 1973. It has a gap 1.5 m high, 2.5 m wide, and 14 m long, with a field of 12 kG at the forward cone, which contains most of the secondaries from the intersection region. Proportional wire chambers will be placed inside the magnet gap and they and other detectors can thus measure the momenta of a large fraction of the particles produced in each individual multiple event. In this way a detailed analysis can be made of each interaction.

CONCLUDING REMARKS

The ISR has opened up a window for elementary-particle research up to 2000 GeV, i.e., far above any existing or planned accelerator. It has also been proven that experimentation with such an instrument is quite possible and the results produced have already started making an impact at international conferences. The main problem is, and will continue to be, the luminosity, but there has been steady progress with good hope that the progress will continue well above present achievement.

The interest raised by the ISR in the physics world is most encouraging, and has already led to serious studies being undertaken of large colliding-beam projects both in the United States and in Europe. Not only does it seem possible to reach higher energies but, with higher energies, it also seems possible to reach considerably higher luminosities.

In short, it looks as if the ISR may turn out to provide the beginning of a very interesting period in elementary-particle physics, and thus fulfil the hopes of those who pressed for its construction.

The project reported on in this paper was constructed by the ISR Department at CERN, a team that had grown to about 300 people at the end of the construction period. This team shared the responsibility for its realization and now shares the success of its early operation. However, during the construction period, there was also continuous help and backing from all other parts of the CERN Laboratory, the CERN Council, and other representatives of CERN's Member States.